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# Self-sustaining Smouldering Combustion as a Waste Treatment Process

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## Abstract

This chapter reviews the utilization of self-sustaining smouldering combustion as a treatment for solid or liquid waste, embedded in a porous matrix. Smouldering has been identified as an attractive solution to treat waste with high moisture content. The fundamental aspects of this technology, such as the experimental setup and the ignition mechanism, are described here.

The operational parameters determine the physical properties of the media, and will dictate the self-sustainability of the process. A discussion on how the operational parameters affect the smouldering performance is also presented. The performance of smouldering is usually assessed by the peak temperatures and the velocity of propagation of the smouldering front through the material.

The potential sources for energy recovery are described. Importantly, as oxidation and pyrolysis coexist during smouldering, it was shown with potential for the recovery of pyrolysis products, such as pyrolysis oil. Finally, a brief insight on the gas emissions, and the perspectives regarding the techno-economic viability in full-scale are also discussed.

**Keywords:** smouldering combustion, self-sustaining, waste treatment, energy recovery, review

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## 1. Introduction

Smouldering is a complex process that involves heat and mass transfer in porous media, heterogeneous reactions at the solid/gas pore interface, thermochemistry and chemical kinetics [1]. It has been historically studied from a fire safety perspective because it represents a fire

risk as the combustion can propagate slowly through the material and go undetected for long periods of time [2]. Smouldering combustion is among the leading causes of residential fires. It is also the dominant combustion phenomena in wildfires of natural deposits of peat and coal which are the largest and longest burning fires on Earth [3].

Nevertheless, the application of smouldering combustion to waste treatment is quite recent. The first paper published using self-sustaining smouldering combustion as a waste treatment alternative is from Vantelon et al. in 2005 [4]. The utilization of smouldering combustion for these purposes opens a new series of questions that needs to be answered. These questions are related, for example, to the experimental setup, the nature of the waste, the characteristics of porous medium, the possibility of energy recovery or the generation of valuable-added products.

The answer to some of these questions is known, while substantial research is required for others. This chapter reviews the state of art on how smouldering combustion can be applied for the thermal treatment of organic waste. The discussion will be almost exclusively centered on issues related to treatment process and does not aim to cover every aspect of smouldering. If the reader wants to go further in depth on the science and theory behind smouldering, the publications of Thomas J. Ohlemiller, who has been studied smouldering for more than three decades, A. Carlos Fernandez-Pello or José L. Torero are strongly recommended.

The main objective of this chapter is to provide the reader a general overview of the self-sustaining smouldering, identifying the main variables that affect the performance and applicability and understanding why smouldering combustion represents an excellent alternative to treat certain type of waste.

The chapter starts defining the concept of smouldering combustion, the mechanisms that govern its ignition and propagation and the main differences with incineration. In Section 2, the fundamental aspects of this technology, such as experimental setup, reactor configuration and ignition mechanisms are presented. Section 3 discusses the conditions necessary to achieve self-sustaining smouldering; and the operational parameters affecting the performance of the smouldering combustion. In Section 4, a description of the possible sources for energy recovery is presented. The potential fuel production from a smouldering combustion treatment is also introduced, showing some examples. Finally, Section 5 discusses the most important issues related to pollutant emissions produced during smouldering; while Section 6 presents the perspectives regarding the technoeconomic viability of smouldering in a full-scale plant.

### **1.1. Smouldering combustion**

Smoldering combustion is a slow, low-temperature, flameless form of combustion sustained by the heat evolved when oxygen attacks the surface of a condensed phase fuel [5]. It has been studied for decades, generally from a fire safety perspective [6, 7] and for a wide range of fuels such as: polyurethane foam [8–13], biomass [14–18], peat [19–23], cotton [24–26], char [27, 28] and mining dumps [29, 30].

A familiar example of smoldering combustion is the glowing char in a barbeque or a burning cigar. Smoldering requires that a fuel be porous as this promotes a high surface area for heat

and mass transfer, insulates the reaction front to reduce heat losses and allows the flow of oxygen to the reaction zone. Ignition is governed primarily by heat transfer and chemical kinetics. The heat supplied during ignition initiates pyrolysis and other endothermic processes, such as evaporation, before oxidation occurs. Propagation will occur when the exothermic oxidation reaction is sufficiently strong to overcome the heat required for pyrolysis and heat losses. If the energy available is not enough, the smoldering will quench and the propagation ceases.

The two limiting factors for smoldering propagation are the oxygen flow and the heat losses [1]. When the reaction is far from its quenching limits, the rate of propagation is directly related to the rate of oxidizer supply to the reaction zone [31]. Close to the quenching limits, heat losses and fuel characteristics can play a significant role. During a waste treatment application, typical heat losses are associated with the presence of water in the fuel, as part of the energy from the exothermic oxidation has to be consumed for water evaporation.

## 1.2. Smoldering applied as a waste treatment

Incineration is a common practice for the disposal of waste to reduce the waste volumes, especially in those countries where land occupation is undesired. The waste management hierarchy, described by United Nations, indicates an order of preference for action to reduce and manage waste. The six levels of the waste hierarchy pyramid (from most to least preferred) are: prevention, minimization, reuse, recycling, energy recovery and disposal [32]. Incineration attends the least favored option in the pyramid of waste hierarchy. In the best case scenario, energy recovery can be achieved by combustion of waste, which is the second least favorable option.

In addition, while pathogens and toxins present in certain hazardous wastes can be destroyed by the high temperatures achieved during flaming combustion (850–1200°C) it usually requires the use of supplementary fuel to maintain the flame and the high temperatures without quenching.

Before flaming ignition can occur, volatiles need to be produced [33]. The characteristic time scales of flaming combustion are on the order of milliseconds while gasification takes on the order of seconds. This means that heat losses from the flame (radiation and convection) are significant resulting in a decrease in flame temperature that eventually leads to quenching [34]. Characteristic reaction times in the flame cannot be changed significantly therefore flame quenching can only be avoided by increasing the energy available to gasify the fuel or by eliminating energy sinks. The latter can be achieved by reducing the water content, insulating the reaction vessel or recirculating hot reaction products, while the former requires addition of supplemental fuel.

A more direct method to achieve time-scale compatibility is to increase the characteristic reaction time by using a slower combustion process, such as smoldering. During smoldering the reaction rate is usually controlled by diffusion of oxygen through the fuel [5, 31]. This means the reaction occurs on a time scale that is comparable with the diffusive transfer of heat away from the reaction zone. Enhanced energy recovery can be achieved by directing the flow

through the porous medium in a manner that allows for the oxidizer flow to be preheated and the combustion products to be used to preheat the fuel. In an idealized one-dimensional framework, this process is known as forward smoldering [8, 13].

The energy efficiency of forward smoldering allows for extended quenching limits [31], as compared to incineration. For this reason, smoldering combustion has gained attention in the last years as a thermal waste treatment for feces [35–40], used tires [4] and vegetable oils [41] and as remediation technique, by treating nonaqueous phase liquids (NAPL) contaminants in soil [41–48].

The temperatures and propagation velocities depend strongly on the operation conditions and the nature of the waste and are generally higher than those observed during fires. With some exceptions, typical peak temperatures for waste treatment processes are in the range 400–800°C and smoldering velocities between 0.1 and 4 cm/min. This temperature range is lower than that in incineration processes (usually from 850 to 1200°C, depending on the waste), but enough to eliminate pathogens and destroy certain hazardous components.

Liquid or pasty fuels can also be smoldered when they are embedded in an inert porous matrix, such as sand or soil. By mixing the fuel with an inert granular material, a porous matrix is created with the necessary heat retention and air permeability properties for smoldering combustion to be self-sustained. Sand is commonly used because it is usually inexpensive and has been identified as an effective agent for increasing the porosity of fuels for application to smoldering treatments [42]. For this reason, from now on in this chapter we will refer interchangeably to sand or porous matrix.

High levels of water content within the organic waste result in a very low effective calorific value. Incineration of this kind of waste requires pretreatment or the use of supplemental fuel to avoid quenching [49, 50]. This means that conventional incineration techniques are uneconomical for these treatments. Importantly, smoldering has been proven as an efficient mechanism for the treatment of waste with high moisture content. For example, it was demonstrated that self-sustained smoldering can be used for the treatment of biosolids with moisture content up to 80% [51].

## 2. Experimental configuration and procedure

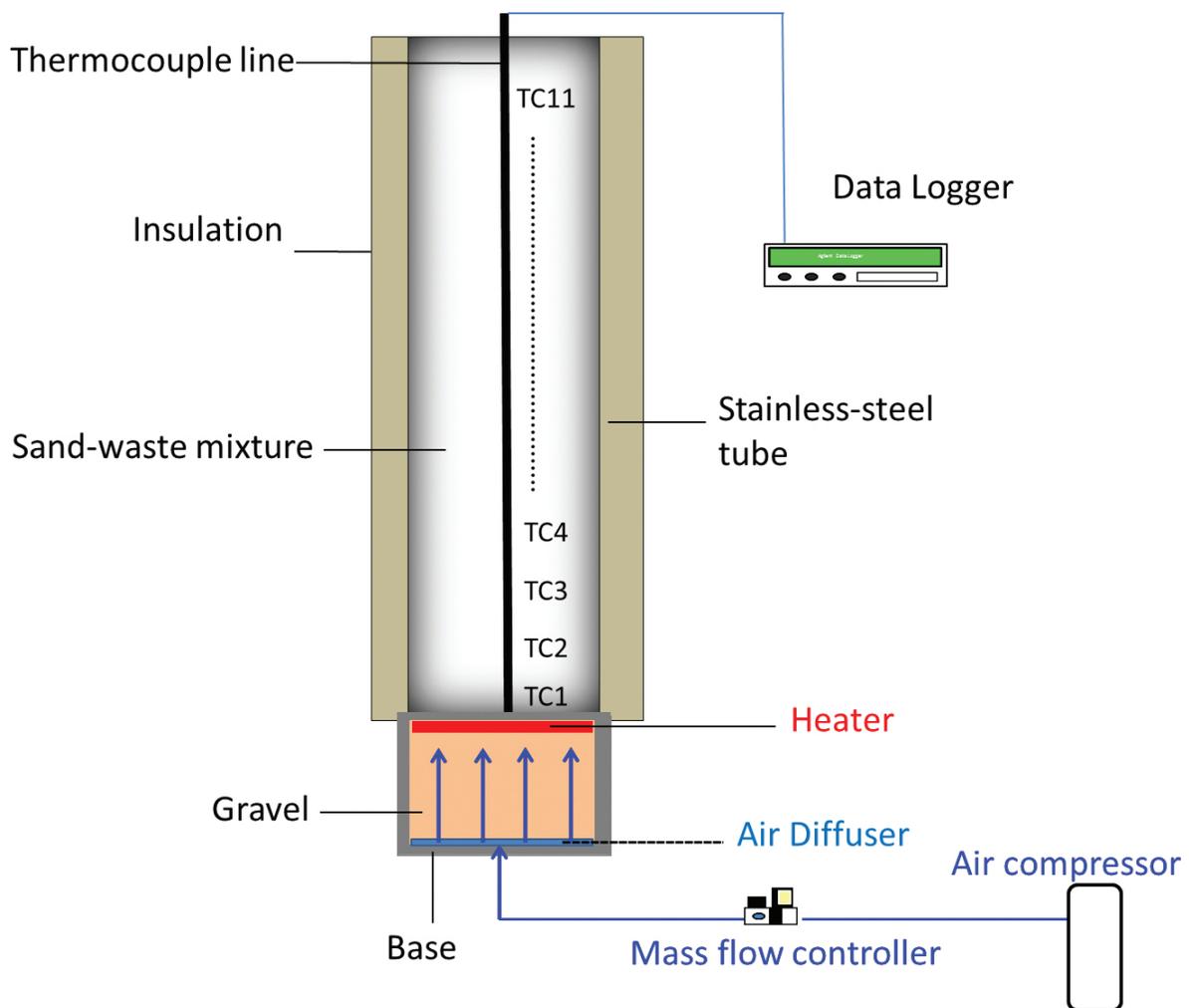
The most common configuration utilized for waste treatments is generally one-dimensional, upwards, forward smoldering. Nevertheless, other configurations are possible. Probably, the most notable example of this is the smoldering combustion of contaminated soil in situ. In this process, the reaction takes place in the ground subsurface, avoiding the necessity of reactors (ex situ smoldering) [48]. However, this configuration is not always possible as the waste-soil characteristics must be suitable for smoldering without pretreatment.

Following, we present a general description of the reaction systems, the ignition procedure and the diagnostics that are generally utilized for smoldering treatment. This section will

restrict the discussion to *ex situ* smoldering. The reader can find a detailed description of in situ smoldering in reference [48].

## 2.1. Smoldering reactors

**Figure 1** shows a schematic representation of a typical smoldering reactor and all its components, in upwards forward configuration. Particularly, the reaction system showed in **Figure 1** has been utilized for the smoldering combustion of feces [35–37, 40, 52]. In this case, upwards smoldering is taking place in a metallic and cylindrical column. The column is placed over a base which houses an electrical heater and air diffuser. These components are covered with layers of gravel to ensure uniformity in the airflow along the cross section of the reactor.



**Figure 1.** Schematic representation of the reaction system used in the smoldering of waste.

The propagation of the smoldering reaction through the reactor is monitored by thermocouples (TCs) positioned along the central axis of the tube. The TCs are connected to a data logger and a computer to register the temperatures as a function of time and height in the reactor.

Other reactor geometries described in the literature are drums and bins, which have been utilized for contaminated soil remediation [46]. Hasan et al. reported two-dimensional experiments and computational simulations for self-sustaining smoldering of coal tar for the remediation of contaminated sand, conducted in a metallic box-shaped reactor [47].

In general, all the smoldering reactors described in the literature are similar to the one showed in **Figure 1**. Even those with different geometries possess the same elements, albeit some components can differ. For example, an horizontal thermocouple configuration has also been used in some cases [12], and the air diffuser can vary from a wide range of configurations (disk [42], ring-shaped [35] or star-shaped tubes [46]).

Variations from the configuration showed can be also in the air supply or in the heating element. For example, the smoldering of used tires has been investigated on a reaction system that uses convective flame heating, while the airflow through the reactor is produced by a fan placed in the exhaust line [4].

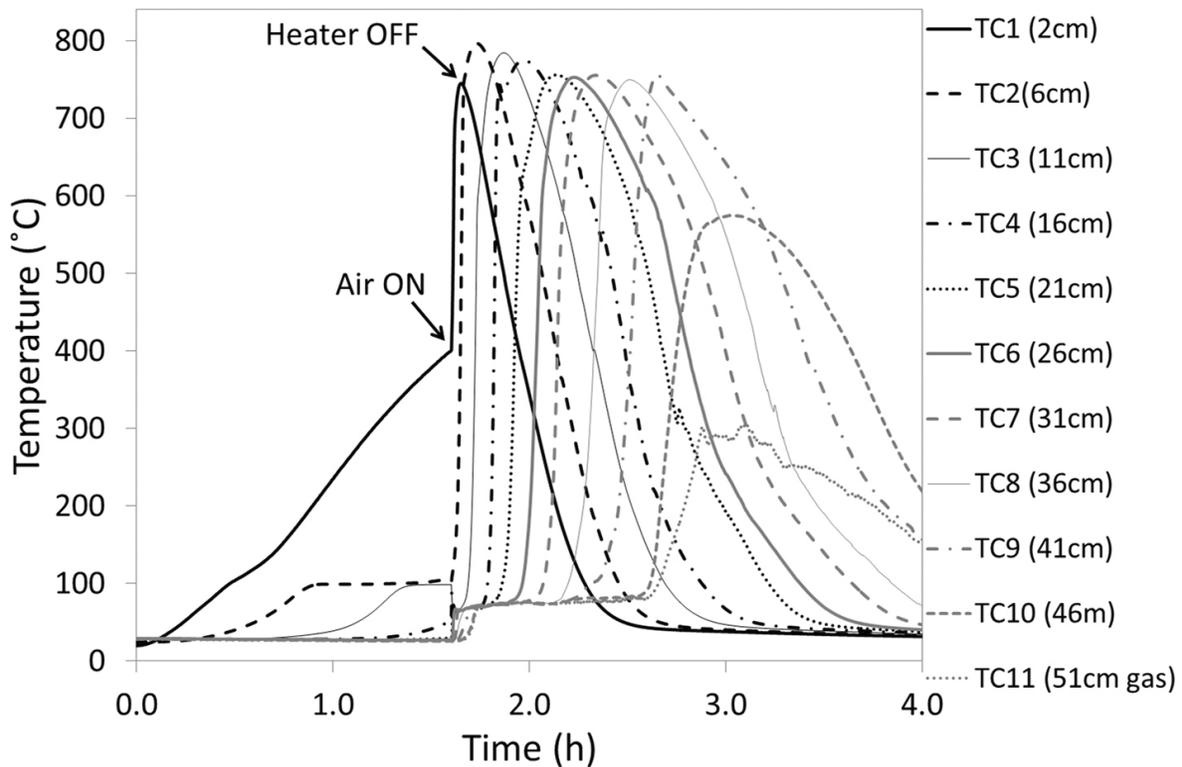
The utilization of convective heating involves higher energy losses and therefore a larger energy input. The efficiency of the convective heater performance can be improved by reducing the heat capacity of the reactor base, improving the heat transfer of the system (e.g., adding insulation to the air injection system) and reducing the airflow rate during ignition [36]. However, despite the higher energy consumption, its implementation can be easier and economically competitive. It can represent an excellent alternative for off-grid applications, or in those places where electricity is expensive.

The pulling-air configuration has been also used, not only to treat used tires but also for the smoldering of feces [38]. As the air permeability of the medium is changing as the waste is being consumed, the utilization pushing-air configuration (mass flow controller) offers much more control on the airflow. However, the pulling-air configuration offers a more economical and easier solution as avoids the utilization of the mass flow controller, tubes and compressed air.

## 2.2. Procedure of ignition and temperature profiles

Typical plots of temperature histories obtained from a self-sustained smoldering combustion treatment can be seen in **Figure 2**. The example shown corresponds to smoldering of organic waste at 65% (wet basis) of moisture content. Initial heating of the bottom layer of waste-sand mixture is achieved by means of the heating element. Once the thermocouple closest to the heater (TC1 in **Figure 2**, at 2 cm from the heater) reaches a certain temperature (400°C in **Figure 2**) the smoldering reaction is initiated by the injection of air. From now on, we will refer to this temperature as ignition temperature or  $T_{ig}$ . It is important that the reader must not misconceive this temperature with the ignition point of the waste.

The heater is turned off once the temperature at TC1 peaks. In this way, ignition of the organic material is ensured. This procedure and configuration yields a robust, repeatable ignition across a wide range of conditions. Ignition protocols can vary depending on the fuel [53].



**Figure 2.** Typical temperature histories of a self-sustaining smoldering test.

In this example the preheating period lasts approximately 90 minutes and is characterized by a gradual increase in temperature up to the desired ignition temperature, and a plateau at 100°C which corresponds to water evaporation. Here, the dominant heat transfer mechanism is conduction due to the electric heater used. Convection and radiation mechanisms are also present at some degree. In this preheating period, as the distance from the heater increases, the duration of this plateau increases. The reason is that more energy is required to evaporate the additional water condensed in the cooler portion ahead. Hence, this plateau is more evident in the temperature profile of TC2 in **Figure 2**.

When the airflow is initiated, the location closest to the heater experiences a sharp increase in temperature up to a peak (close to 750°C in **Figure 2**) as rapid exothermic oxidation of the dried and pyrolyzed fuel occurs. At this moment, convection becomes the dominant mechanism as the hot gases move upwards. The adjacent TCs experience a temperature increase due to the convective heat transfer from the reaction zone to the virgin material ahead.

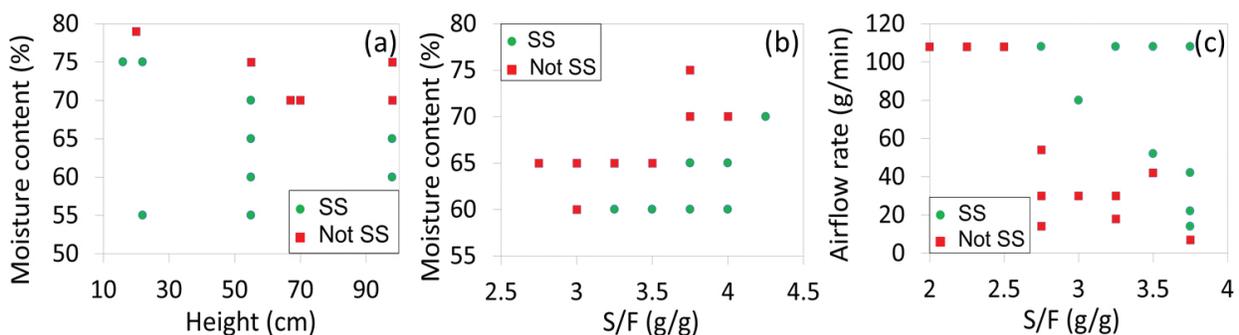
In the combustion zone, as the reaction front approaches, only a minor plateau is observed at 100°C indicating that the heat flux from the combustion zone is enough to rapidly dry the mixture ahead. In **Figure 2**, this is more evident for TC9, at 41 cm from the heater. The material is thus predried ahead of the smoldering front's arrival. As the fuel is consumed and the reaction at that location stops, the temperature falls as it is cooled by incoming air. The

succession of temperature peaks is observed throughout the mixture is indicative of a self-sustaining smoldering reaction.

Due to the high moisture content of the material, the example showed in **Figure 2** is among the most complex smoldering treatments. In the case of treating dry waste, the plateaus aforementioned are not seen as evaporation and recondensation of water do not occur.

### 3. Parameters affecting the smoldering performance

Several papers in the literature have systematically studied the influence of the key parameters affecting the smoldering performance, which is generally assessed in terms of self-sustainability, average smoldering velocity and average peak temperature. For example, He et al. studied the influence of the fuel characteristics on the smoldering of biomass powder [16]; Pironi et al. studied the influence of the airflow, fuel saturation and sand characteristics on the smoldering of NAPLs and coal tar; Switzer et al. addressed the scaling effects on the same reaction [46]. Regarding wastes with high moisture content, Yermán et al. investigated the influence of all these parameters on the smoldering combustion of feces [35, 40, 52, 54], while Rashwan et al. [51] mapped the parameter space for smoldering of biosolids and studied the influence of waste nature and airflow. For every operational parameter, there is a range where self-sustaining smoldering is possible. The velocity of smoldering is an important factor in waste treatment processes as it is related to the waste consumption rate and hence will determine the necessary reactor scale. The smoldering temperature is related to the possibility of energy recovery, heat losses and insulation required and gas emissions.



**Figure 3.** Parameter space outlining the range of conditions yielding self-sustaining (SS) and not self-sustaining (not SS) smoldering: (a) moisture content versus height of sand-fuel mixture, (b) moisture content versus sand-to-fuel mass ratio (S/F), (c) airflow rate versus sand-to-fuel mass ratio (from [35]).

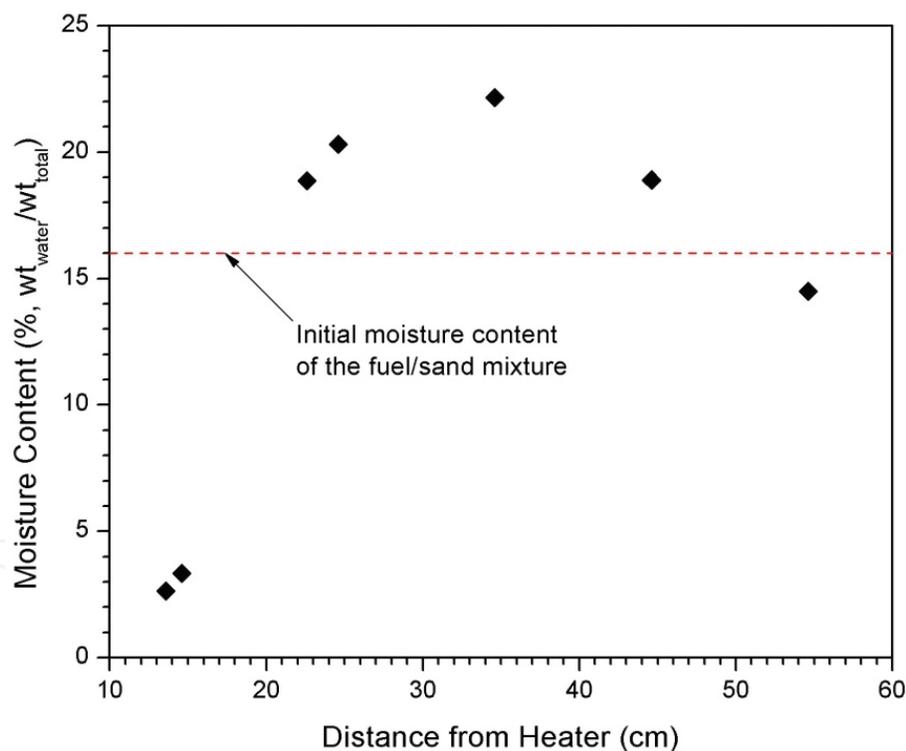
The ranges of self-sustainability for each parameter are not independent; rather they are interdependent in a complex manner. In practice, it is necessary to identify the parameter space in which a robust self-sustaining process will operate. As an example, **Figure 3** shows the interdependency of some of these parameters for the smoldering of surrogate feces mixed with sand [35]. A parameter space has been mapped for conditions yielding to self-sustaining

smouldering by varying moisture content, sand-to-fuel pack height, airflow rate and sand-to-fuel ratio.

For example, these results showed that if the moisture content of the waste is increased, then the pack height of mixture in the reactor must be shortened and the sand concentration increased. A similar situation occurs with the relationship between airflow rate and sand concentration, where higher sand concentrations allow lower airflow rates. Following, the influence of these and other key parameters on the smouldering performance will be treated in more detail.

### 3.1. Moisture content

The moisture content of the feces is an important energy sink that affects the ignition [20], and the conditions under which sustained smouldering will occur without quenching [55]. Water evaporation during smouldering represents an important energy sink. Close to quenching limits, moisture content is a crucial parameter for the self-sustainability of the smouldering propagation.



**Figure 4.** Moisture distribution of the sand-fuel mixture above the reaction zone for a non-self-sustaining test of feces mixed with sand at 75% moisture content (from [35]).

Additionally, studies showed that water recondensation in the layers of cooler mixture above the smouldering front can be significant [35]. This situation provokes an increment in the local moisture content levels. Moreover, free water flowing down inside the column can occur and can lead the reaction to quenching. **Figure 4** shows the moisture content at different heights

in the reactor after excavation of the mixture in a non-self-sustaining smoldering test. Water accumulation can be clearly seen above 20 cm, and is responsible for the experiment's quenching.

Reference [35] demonstrates that the limit of moisture content for a self-sustaining smoldering process depends on the pack height of mixture inside the reactor. The mixture pack height affects the time-varying distribution of moisture content. This happens in two ways: (i) from a thermal perspective, a longer pack of cool material favors increased degree of recondensation ahead of the reaction front; (ii) from a hydraulic perspective, recondensed water is unbound and a longer pack can generate a higher hydrostatic pressure at the moisture front leading to more significant drainage downwards into the front. Therefore, quenching can be avoided by using a shorter pack of sand-waste. Furthermore, other possibilities are predrying the waste or mixing it with other waste streams to increase the average calorific value. However, both alternatives require energy for implementation.

Far from quenching limits, the effect of moisture content in the performance of the smoldering experiments was studied for different types of waste [16, 40, 44]. Experimental observations showed that the velocity of smoldering propagation is not affected by the moisture content of the medium. This independence is somehow expected since the propagation of the smoldering reactions occurs on completely dried [20]. Regarding the smoldering peak temperatures, as water acts as an energy sink, a reduction in the peak temperatures can be expected when moisture content increases, as reported in [44] (up to 200°C within the range of self-sustainability). Still, variations of 10–20% in the waste moisture do not produce significant differences in the observed peak temperature [16, 40].

### 3.2. Porous medium

Inert porous media that have been used for waste treatment applications are: sand, soil, a mixture of both, gravel and refractory briquettes. By far, the most common inert porous medium used in waste treatment processes is sand because is inexpensive and commonly available. Agricultural waste has also been used for the smoldering of feces, however its use is only reported and there is no systematic study on the influence on smoldering performance [36]. While the nature of the porous medium may have also an influence on the smoldering performance, this is not addressed in the literature.

The effect of the porous medium on the smoldering performance can be explained because it affects the air permeability of the waste-porous medium mixture. This influence can be described through the porous medium concentration and the particle size. Both parameters have been investigated.

#### 3.2.1. Concentration

The concentration of porous medium in the smoldering mixture determines the air permeability of the mixture matrix and hence, its self-sustainability. If the concentration is too low, the air permeability of the medium may not be sufficient for the oxygen to reach the fuel in the surface of the porous medium, and smoldering will not propagate. If the concentration is

too high there is a critical condition where there is not enough fuel (waste) to overcome heat losses and sustain the smoldering reaction.

As **Figure 3** shows, the operational window for sand concentration (expressed as sand-to-fuel mass ratio) is reduced if, for example, the airflow is reduced. Within the range of self-sustainability, the smoldering performance is affected by the porous medium concentration. Both smoldering temperatures and propagation velocities decrease when the sand concentration increases.

As the sand concentration increases, there is less fuel per length unit. This decreases the energy release rate and therefore the smoldering velocity. As the porous medium is generally inert and not combustible, part of the energy released from the exothermic oxidation has to be consumed on heating the porous medium and therefore, it acts as energy sink. This provokes that the smoldering temperatures also decrease when the porous medium concentration increases [40, 44].

### 3.2.2. Particle size

A similar situation occurs with the influence of the particle size. A window of particle size can be identified where self-sustaining smoldering is possible. At low particle sizes, the fine particles do not provide enough air permeability to the mixture. At the other extreme, when the particle size is too high, the hot gases pathway towards the end of the reactor is short, and therefore the energy is not efficiently transferred from the smoldering front to the portion of mixture ahead.

This was confirmed by some experimental observations where the temperature of the exhaust gases was higher when using gravel instead of sand as porous medium. These hotter gases leaving the reactor take away part of the energy which is required for the self-sustaining propagation.

Smoldering performance as a function of the particle size was studied for the combustion of feces [40] and coal tar [44] mixed with sand/gravel. Both the temperature and smoldering velocities decrease when the particle size increases towards the critical value. However, this parameter appears to be the one with the least impact on the peak temperatures and smoldering velocities, at least among those that were systematically studied. Those papers described a slight variation of smoldering temperatures and velocities (not more than 36%) within the range of self-sustainability. Pironi et al. [44] suggested that it might be balance between the expected increment in the smoldering velocity due to the increment in the fuel surface area per unit volume, and the decreased fuel concentration.

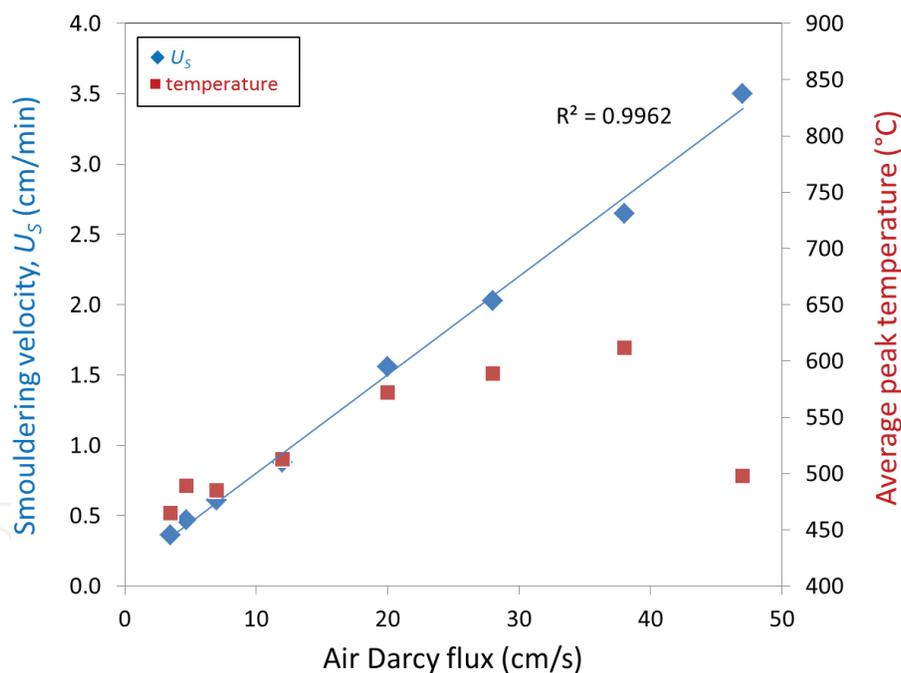
### 3.3. Airflow rate

Smoldering requires oxygen to sustain the exothermic oxidation reactions. Thus, there is a minimum oxygen concentration in the smoldering front required for propagation. This minimum concentration is mainly a function of the air permeability of the propagation medium. Above that threshold, the oxygen concentration will always be enough for

self-sustaining propagation. While there are some studies on the influence of the oxygen concentration on smoldering [56], all waste treatment processes utilize atmospheric air. On the other extreme, at very high airflows there is a critical condition that can enable transition to flaming. This transition depends on the scale, moisture content and characteristics of the fuel.

There is enough evidence that the rate of propagation is directly related to the rate of oxidizer supply to the reaction zone [31]. Switzer et al. studied the smoldering remediation of NAPL-contaminated materials [46] and found that the remediation time can be controlled by the air injection rate, with higher rates leading to higher propagation velocities. The correlation seems to be linear in experiments performed with different reactor geometries.

In another work, Yermán et al. found a clear linear relationship between the airflow and the smoldering velocity during the smoldering of feces mixed with sand. Authors reported a linear regression of 0.996 within an airflow range where the airflow is increased more than 13 times (see **Figure 5**). Airflow is the parameter with higher impact on the smoldering performance. As the example shows, just modulating the airflow, the smoldering propagation velocities can be changed by more than one order of magnitude.



**Figure 5.** Average peak temperature and smoldering velocity ( $U_s$ ) as a function of air Darcy flux for self-sustaining smoldering experiments of feces mixed with sand (from [40]).

Regarding the peak temperatures, these tend to increase at low airflows and decrease at high airflows, as **Figure 5** shows. This is mainly associated with the fine energy balance between heat transfer and the heat release rate from the exothermic oxidation. Increasing the airflow implies higher heat release rate, which raises the temperature inside the reactor. On the other hand, at high airflows, it was observed that the temperature of the gases leaving the reactor

increases with the airflow. This means part of the energy is leaving the reactor with the exhaust gases. Due to the high velocity of the gas inside the reactor, the heat from the exothermic reaction is not efficiently transferred to the mixture inside the reactor, and the observed temperatures are lower. A similar behavior was reported for the smoldering of coal tar [42].

### 3.4. Others

#### 3.4.1. Scale

During smoldering, heat losses are linked to process scale. Heat losses diminish when the scale is increased due to the lower surface-to-volume ratio. Consequently, the operational window where self-sustaining smoldering can be possible is extended at larger scales (e.g., higher moisture content).

Smoldering temperatures are also usually higher at larger scale due to the reduced heat losses. However, the propagation velocities are not necessarily affected. This was observed in [52] where the smoldering of surrogate feces was studied under the same operational conditions, reactor geometry, but different scales. While the smoldering velocity does not change with scale for the same operational conditions, the waste consumption in mass per time unit increases with the size of the reactor. This is an important observation for scaling-up the smoldering technology, as the waste consumption rate can be predicted from laboratory-scale tests.

#### 3.4.2. Ignition temperature

It is important to remind the reader that ignition temperature was defined as the temperature where the airflow is initiated. Reports showed that the airflow can be initiated at temperatures that are considerably below the spontaneous ignition of the waste, even at ambient temperature [36, 40].

Those studies also showed that there is no influence of the ignition temperature on the smoldering performance. Therefore, as it is always desired to operate this technology with the least energy consumption as possible, the situation where the energy consumed during ignition is the lowest should be chosen and determined for every case.

A higher ignition temperature is usually associated with a larger energy input from the heating element. However, this is not the case at low (close to ambient) ignition temperatures. When the airflow is initiated at low temperatures, the sand-waste mixture is then cooled by the incoming fresh airflow. Hence, more energy (and time) from the heating element will be required to achieve combustion of the organic waste.

## 4. Energy recovery

There are several sources for potential energy recovery from a smoldering combustion process. These are: (i) steam condensation, (ii) hot sand, (iii) hot gases and (iv) fuel production.

### 4.1. Steam condensation

Steam condensation represents an attractive source of energy, especially when the waste to treat has high moisture content. In some cases, the energy recovered from condensation can be as large as the energy required for ignition [36].

Another example of this is one of the prototypes presented for the Reinvent the Toilet Challenge launched by The Bill and Melinda Gates Foundation. This prototype is a sanitation mechanism for disinfection of human waste that relies on the smoldering combustion of feces. In this system, the steam generated from flash drying of the feces, before condensation, is used in a heat exchanger to pasteurize the urine and liquid waste from the toilet, maintaining the temperature between 65 and 75°C for several hours [38].

### 4.2. Hot sand

After the smoldering treatment, the sand obtained is clean and hot. In general, only a slight change in color is observed [35, 36, 43, 52]. This is usually attributed to the oxidation of the iron compounds in the sand [42].

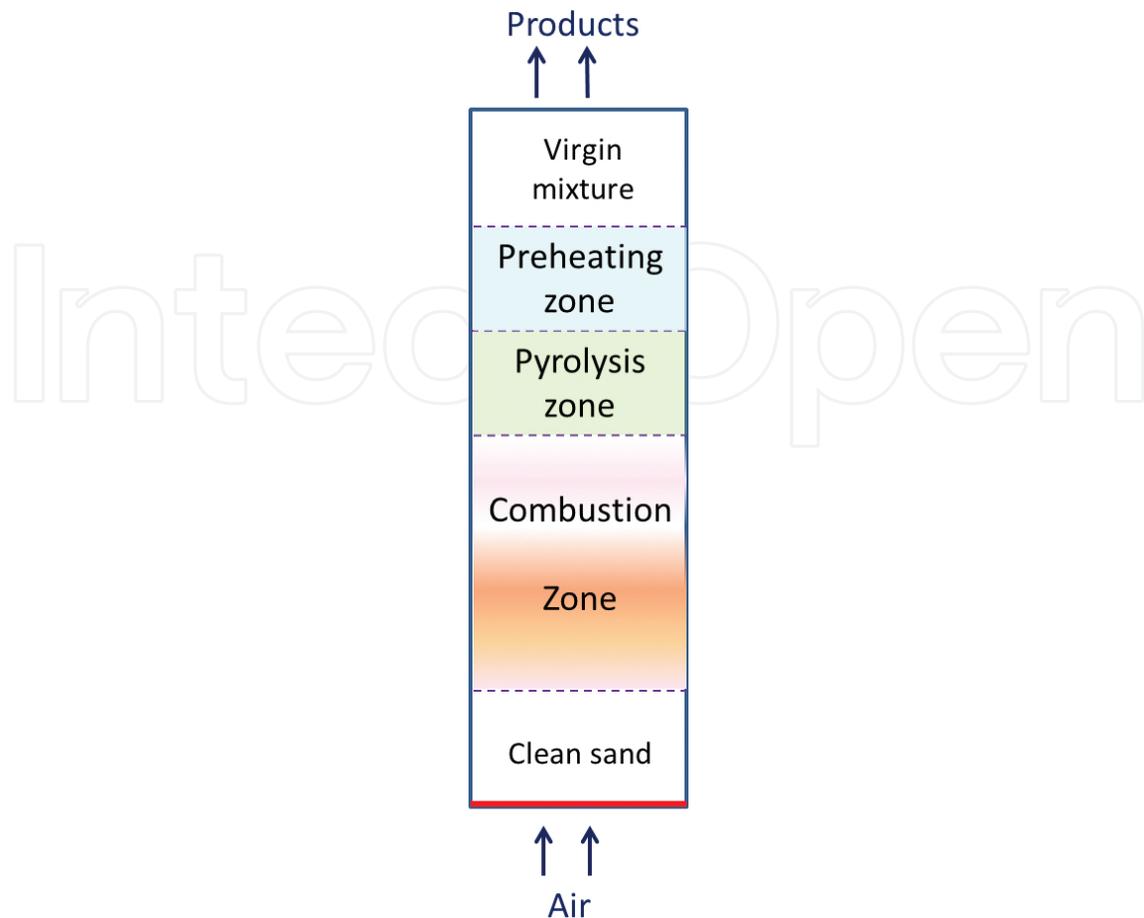
The hot sand represents an important heat source than can be used, for example, to predry the next batch of waste. In the case of smoldering of feces, it was demonstrated that sand can be reutilized for at least five consecutive treatments [36] without impact on the smoldering performance. The presence of fine ashes within the inert porous matrix will decrease the air permeability of the sand-waste mixture, reaching eventually a critical condition where propagation of smoldering combustion is not possible. The ash accumulation is a function of the inorganic content in the waste, and the sand concentration used for the smoldering treatment.

### 4.3. Fuel production

The low temperatures of the smoldering reactions generate the potential recovery of pyrolysis products. Pyrolysis oil production from smoldering combustion processes has been assessed for used tires [4] and feces [57].

**Figure 6** shows the different zones that can be distinguished during smoldering, inside the reactor and can help to understand how and where the pyrolysis products are produced. The first region (bottom) is defined as the region where the fuel has been consumed by the passing smoldering front (combustion zone). Ahead of the smoldering front heat is transferred via conduction, convection and radiation to the unreacted sand and fuel. In this region, the oxygen concentration is considerably depleted and heat is consumed in the endothermic pyrolysis of the fuel. As the available heat decreases, the temperature eventually reaches a critical point where pyrolysis cannot be sustained (usually 200–300°C).

The end of the pyrolysis zone marks the beginning of the preheating zone where heat is consumed through preheating of the unreacted zone. As the available heat decreases, the temperature eventually reaches ambient temperature, which delineates the end of the preheating zone. After that zone, only virgin sand-fuel mixture is present.



**Figure 6.** Zones that can be distinguished during smoldering and inside the reactor (modified from [57]).

The yield of pyrolysis products during smoldering can be maximized if pyrolysis temperatures are maintained in the zone of low oxygen concentration. In other words, the larger the pyrolysis zone is, the higher the amount of pyrolysis products obtained.

The extension of the pyrolysis zone can be increased if the fuel is dry and has a high calorific content, providing more energy available for pyrolysis and reaching higher temperatures. Comparing the two aforementioned examples, rubber tires have a calorific content about eight times higher than wet feces. That study observed that the oils exhibited a mass percentage yield of 35% relative to the tires. Maximum oil recovery was observed at the minimum smoldering velocity. On the other hand, maximum oil yield from smoldering of feces was only 7% relative to the mass of dry feces. In this case, pyrolysis oil yield seems to increase with the airflow rate, although the relationship is not completely clear.

## 5. Gas emissions

The potential for the formation of harmful compounds exists in every smoldering process, especially when the waste represents an environmental hazard (e.g., coal tar). As in an

incineration process, the gas emissions must be assessed and controlled or captured. In the same way, gas emissions can vary significantly depending on the waste nature, oxygen excess and other operating conditions. Nevertheless, some general features associated with the effluent gas composition can be addressed.

It is of great importance to notice that the gas emissions associated with smoldering differ significantly from those produced during flaming combustion. Yet, the same standard gas treatment practices can be applied in both cases. As pyrolysis and oxidation coexist during smoldering, smoldering produces higher amount of hydrocarbons and CO than incineration. For example, Rein et al. found that the CO/CO<sub>2</sub> ratio is approximately 0.4 during smoldering, while it is approximately 0.1 in flaming combustion [22, 58]. In addition, Switzer et al. report CO/CO<sub>2</sub> ratios of 0.1–0.7 when using smoldering for remediation of NAPL-contaminated soil [46].

Pyrolysis products, which are usually oxidized in the presense of flaming combustion, contribute significantly to the gas emissions during smoldering. These products include hydrocarbons, volatile organic compounds (VOCs) and polyaromatic hydrocarbons.

While quite a few papers on emissions during natural smoldering can be found in the literature, there are not many scientific reports on emissions during smoldering combustion applied to waste treatment. Scholes et al. report total VOCs between 47 and 88 g/L for the smoldering remediation of coal-tar-contaminated soils [48]. While these values can be higher than those during incineration, they are considerably below the VOC emissions during composting of waste [59] or from typical manufacturing industries [60].

Regarding production of NO<sub>x</sub> and SO<sub>x</sub>, Switzer et al. studied the smoldering combustion of nonaqueous phase liquids mixed with sand and soil. Nitrogen and sulfur oxides were not detected above the threshold of 1 ppm [43]. It is preassumed that this is due to the lower temperatures during smoldering as compared to incineration, although further and extensive research is needed in this matter.

## 6. Technoeconomic viability

As for any other technology, the technoeconomic feasibility for applying smoldering as a waste treatment process must be assessed for every particular case, and compared to other possible alternatives. Applicability scenarios can be very different, and many factors should be taken in consideration for a technical analysis, that every particular case must be considered separately. For example, the aim of the treatment (e.g., environmental hazard, volume reduction, dewatering, metal or nutrients recovery) is strongly related to the economic return. In this section, the general considerations and critical issues to take into account when performing technical and economic analyses are presented.

At present, soil remediation is the only full-scale and real application of smoldering as a waste treatment process [48]. Nevertheless, current investigations on the topic demonstrate that the

technology is economically feasible for other applications. In the close future, smoldering is envisaged as an alternative for the treatment of many waste streams.

As a general rule, smoldering is a suitable alternative for reduction of waste volumes, especially for waste streams with high moisture content. Furthermore, it is an attractive option to treat hazardous waste, as the high temperatures ensure pathogen destruction. In both cases, the thermal treatment should be performed on site. In the former case, this would avoid important transportation costs as highly wet waste usually comprises large volumes, and in the latter, it would elude the impracticality of handling hazardous materials.

In general, the technical feasibility can be usually assessed at laboratory scale, as the higher heat losses make this scale a conservative scenario. As the smoldering velocity does not change with the scale, the operating conditions and size of the reactor for a full-scale application can be easily extrapolated from those laboratory tests. The full-scale of this technology depends on the waste production rate and also on the type of waste. While accumulation of waste may be possible in some cases to generate adequate volumes, this is not always feasible. If the aim of the treatment is the elimination of pathogens – as can be the case of feces, animal waste or hospital residues – then the destruction has to be almost immediately, and the scales required are smaller. For example, a toilet that smolders feces should operate in the range of kilos per day, as compared with agricultural waste or contaminated soil that must operate in the range of tons per day.

For the economic analysis, the expenses to consider are: equipment, installation, operation, maintenance and reduction of fees paid for the disposal of waste. Equipment, installation and maintenance are substantially the same for every smoldering application. However, maximum temperatures and corrosiveness of the waste can determine the necessity of different reactor materials and wall thicknesses. The operation costs are mainly associated with waste pretreatment, mixing, ignition and reactor loading/unloading. Waste pretreatment can include: adaptation of the waste particle size (in the case of solid waste) or predrying (for liquid or pastry waste).

The potential sand reutilization and energy recovery must be also considered in the economic analysis, as they would reduce the operative costs. The operating conditions of smoldering should be chosen to maximize the benefit from these. There are other issues to consider that may have impact on the operating conditions. For example, heterogeneity of the waste is inevitable and because of this the smoldering must operate far from quenching conditions. Also, the possibility of mixing the waste with other waste streams should also be considered. This can have two benefits: reduce/avoid sand utilization and increase the calorific value (and/or reduce the moisture content).

Finally, additional profit can be obtained from environmental benefits. Still, environmental issues must also be carefully taken in consideration. For example, smoldering applied to soil remediation can bring massive benefits, as avoids the contamination of water resources. On the other hand, losses of nitrogen and carbon in the soil result in a poor soil for plant growth, and further soil rehabilitation is needed [61].

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## Nomenclature

NAPL	nonaqueous phase liquids
S/F	sand-to-fuel mass ratio
SS	self-sustaining
TC	thermocouple
$T_{ig}$	ignition temperature
$U_s$	smoldering propagation velocity
$U_s$	smoldering propagation velocity
VOC	volatile organic compounds

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